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G02B 17/04  
USPC ..... 73/861.18, 861.28, 861.27; 702/48;  
340/606  
See application file for complete search history.

- (56)
- References Cited**

- U.S. PATENT DOCUMENTS

- |              |      |        |              |           |
|--------------|------|--------|--------------|-----------|
| 2014/0109645 | A1 * | 4/2014 | Ramsa .....  | 73/1.34   |
| 2014/0109686 | A1 * | 4/2014 | Ramsay ..... | 73/861.18 |
| 2014/0109689 | A1 * | 4/2014 | Ramsay ..... | 73/861.28 |
| 2015/0000420 | A1 * | 1/2015 | Ramsay ..... | 73/861.01 |

- \* cited by examiner

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- (57) **ABSTRACT**

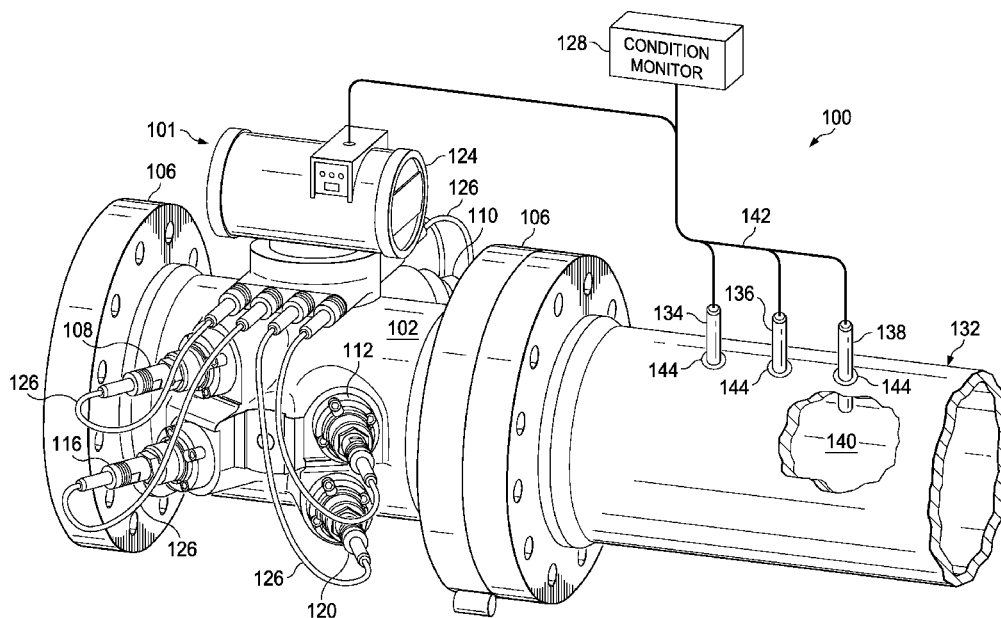
- Apparatus and methods for monitoring operation of an ultrasonic flow meter. In one embodiment, an ultrasonic flow metering system includes a passage for fluid flow, an ultrasonic flow meter, and a condition monitor. The ultrasonic flow meter is configured to measure transit time of an ultrasonic signal through the fluid flowing in the passage. The condition monitor is coupled to the ultrasonic flow meter and is configured to monitor a parameter of ultrasonic meter operation with respect to Reynolds number. The condition monitor is further configured to determine whether a value of the parameter at a Reynolds number of the fluid flowing in the passage at a time associated with the value is within a predetermined range of values for the parameter at the Reynolds number.

**20 Claims, 8 Drawing Sheets**

- (60) Provisional application No. 61/716,147, filed on Oct. 19, 2012.

- (51) **Int. Cl.**  
**G01F 1/66** (2006.01)  
**G01F 25/00** (2006.01)

- (52) **U.S. Cl.**  
CPC **G01F 1/66** (2013.01); **G01F 1/662** (2013.01);  
**G01F 25/0007** (2013.01)



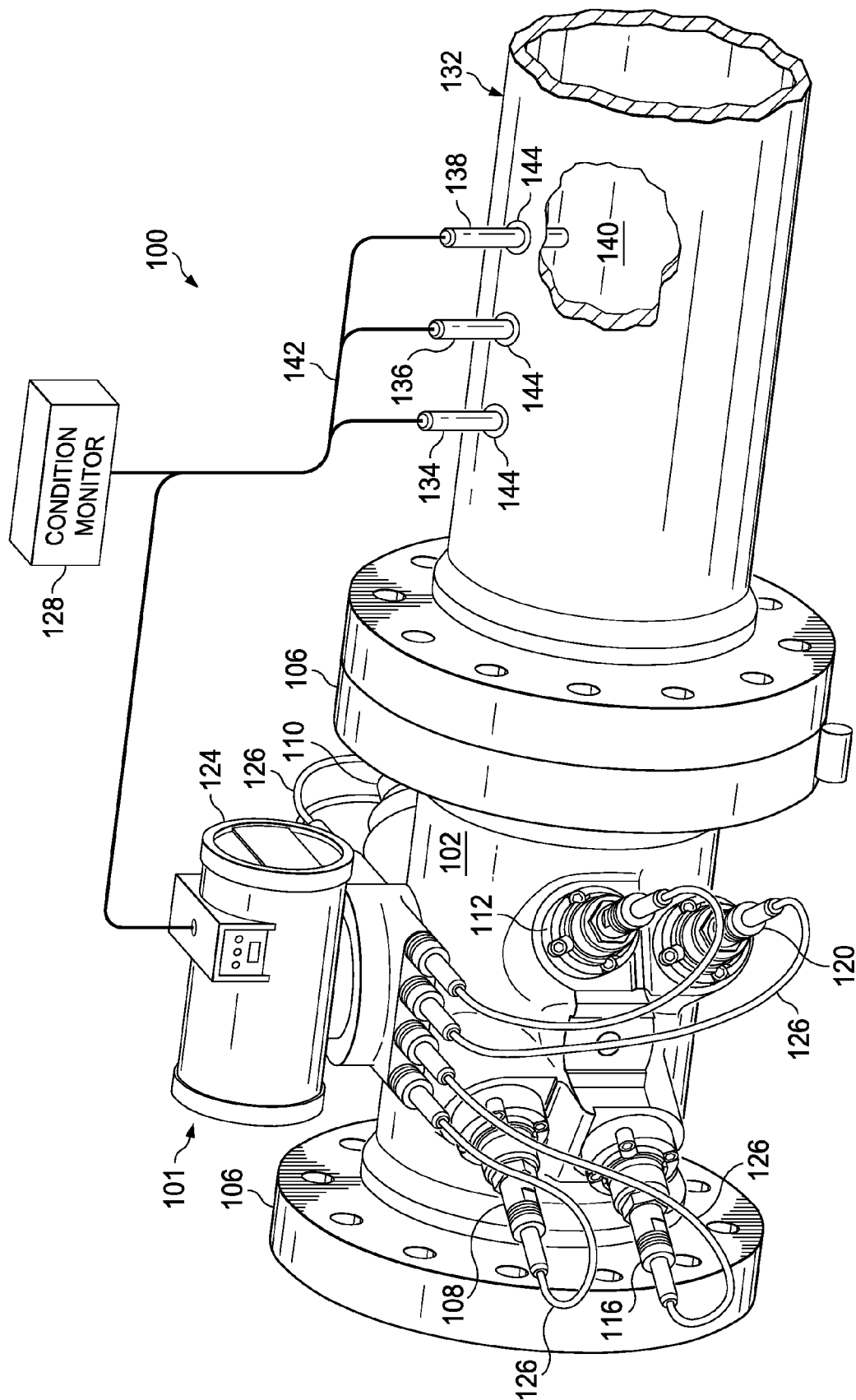
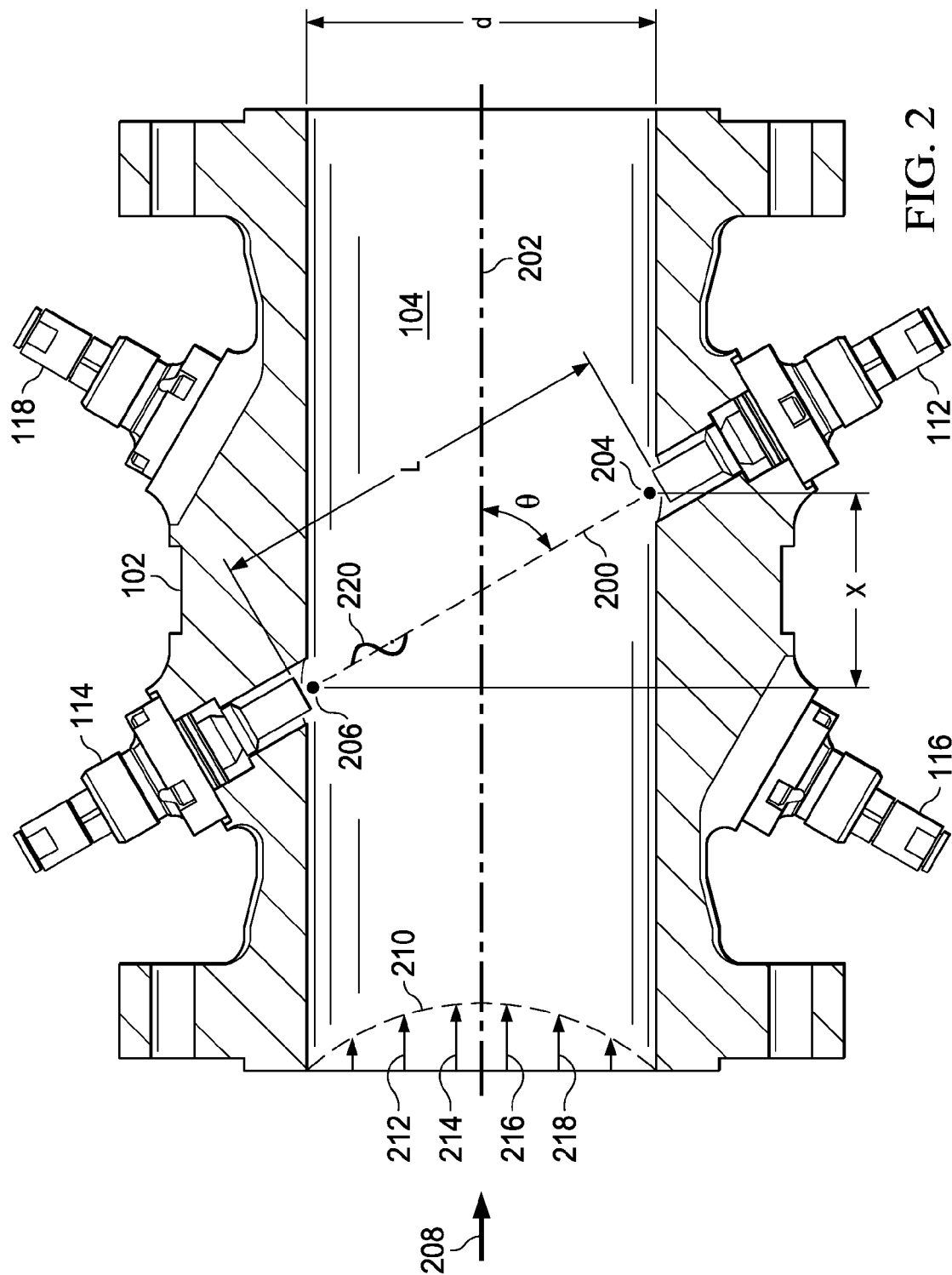


FIG. 1



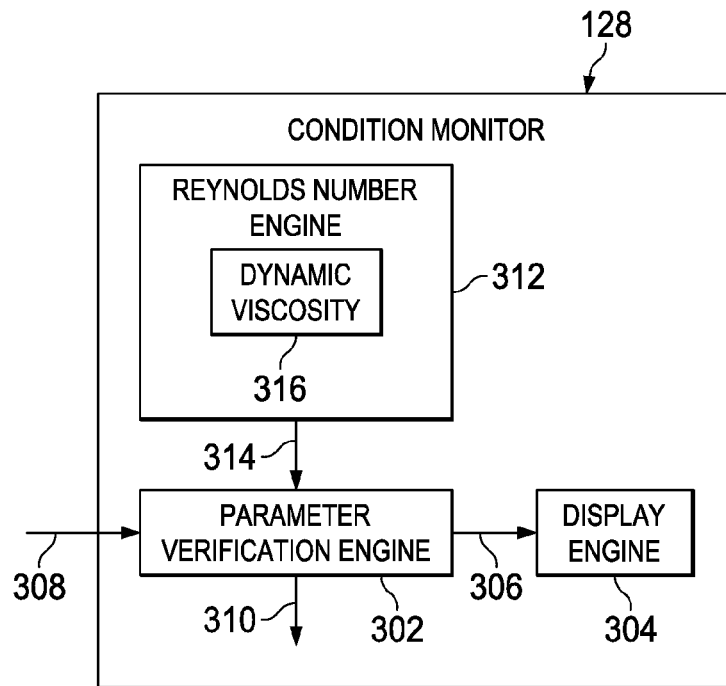


FIG. 3

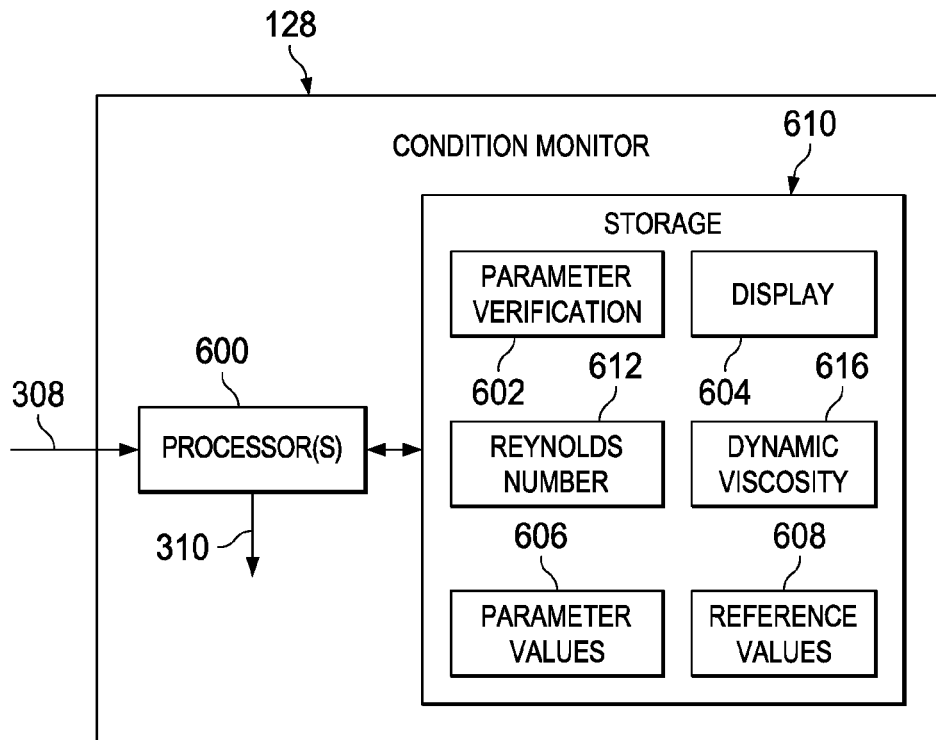


FIG. 6

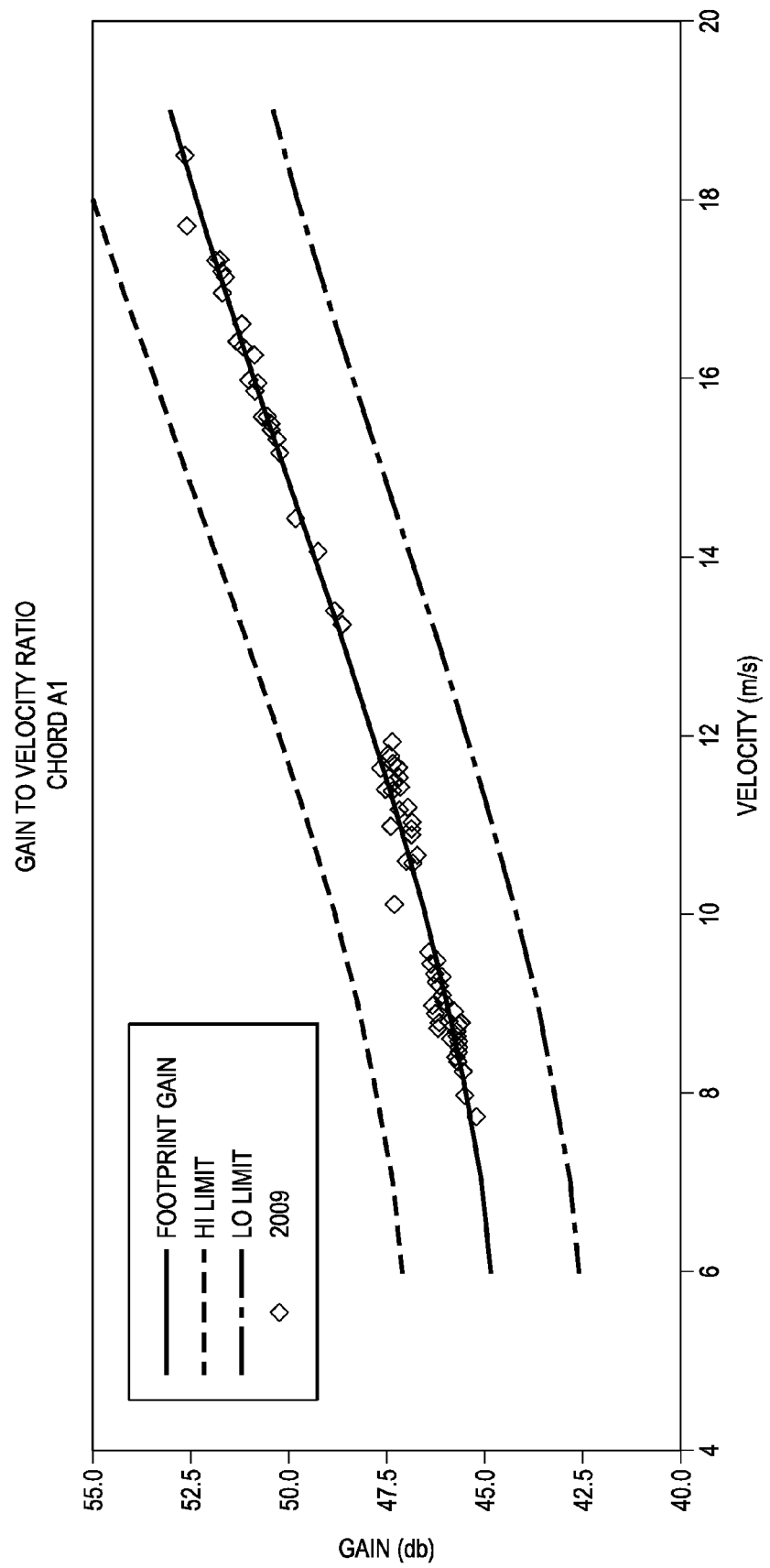


FIG. 4A

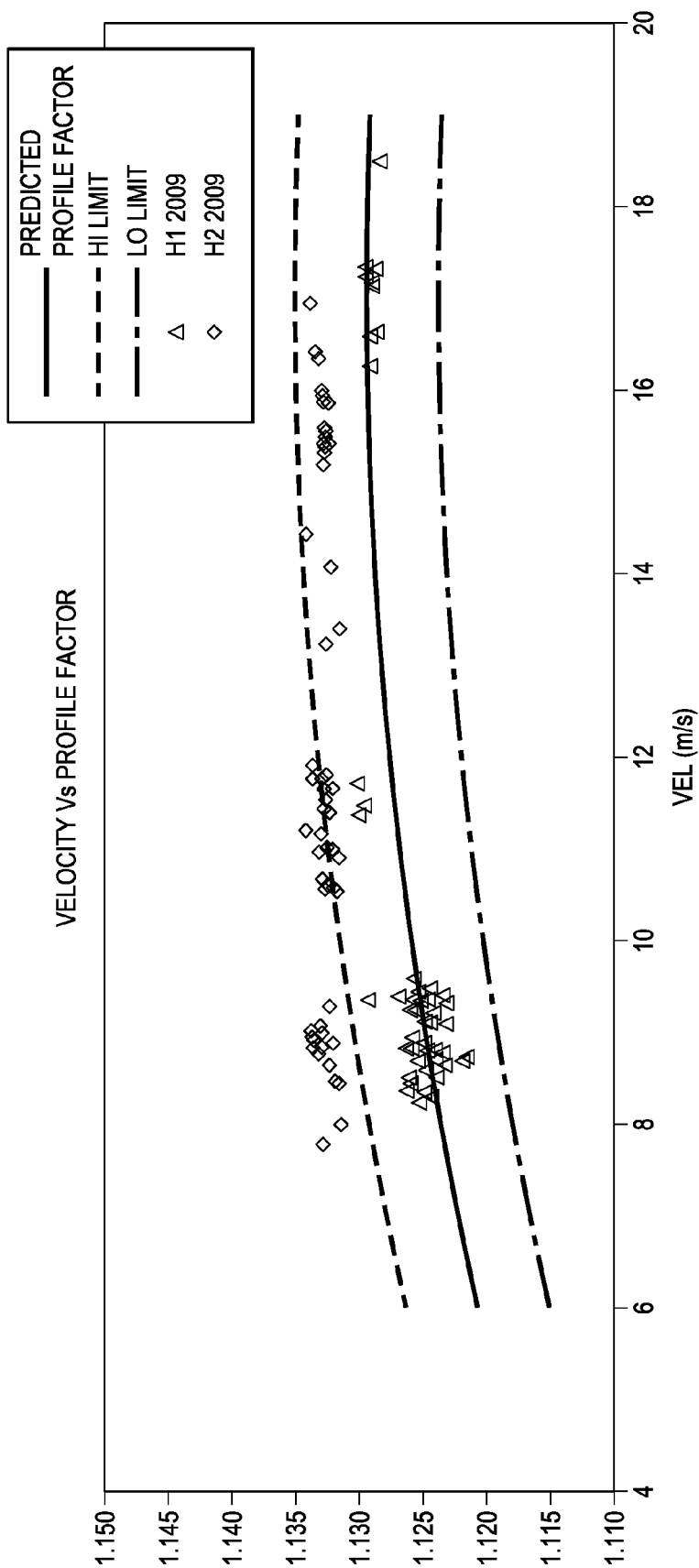


FIG. 4B

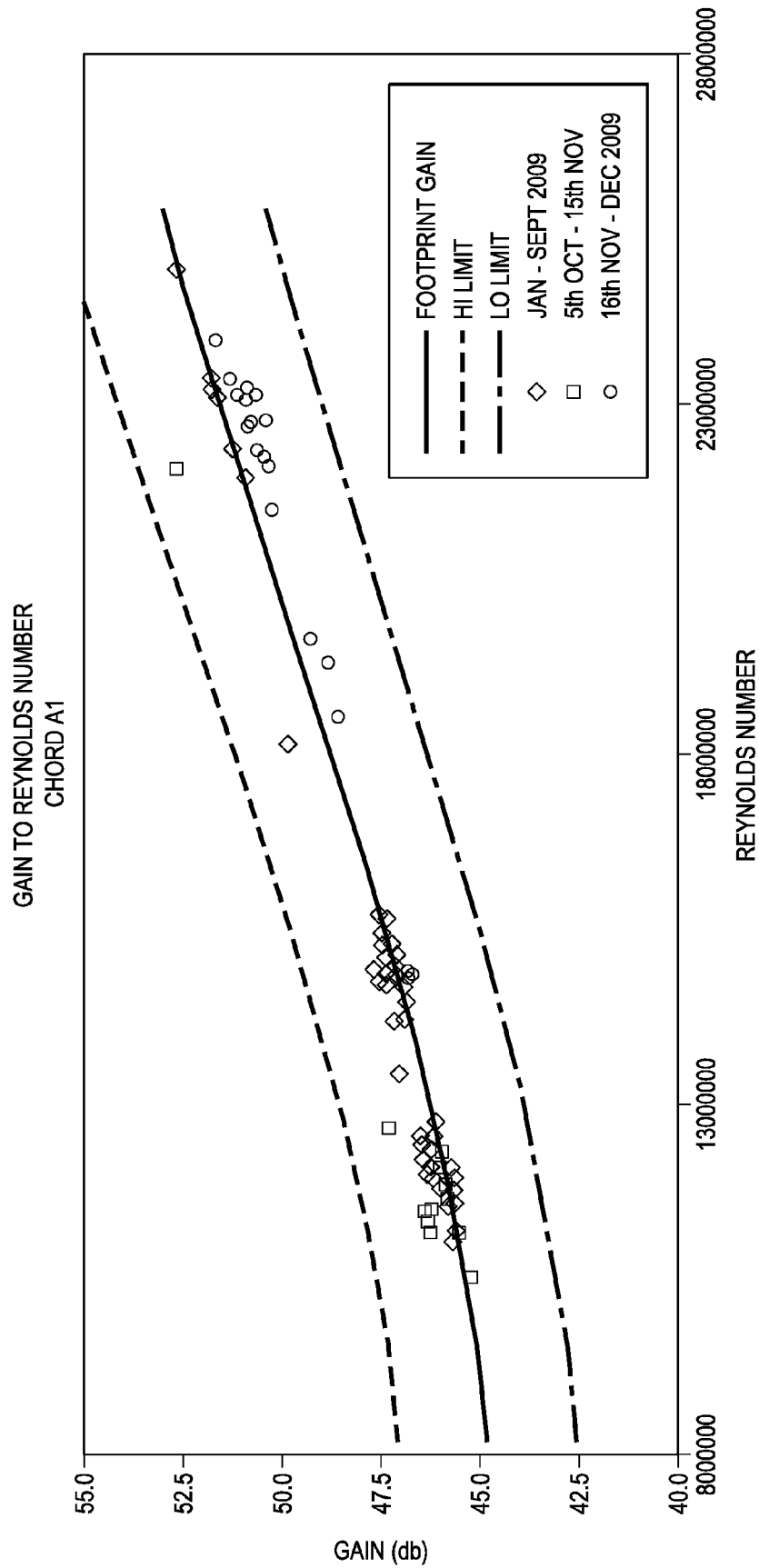


FIG. 5A

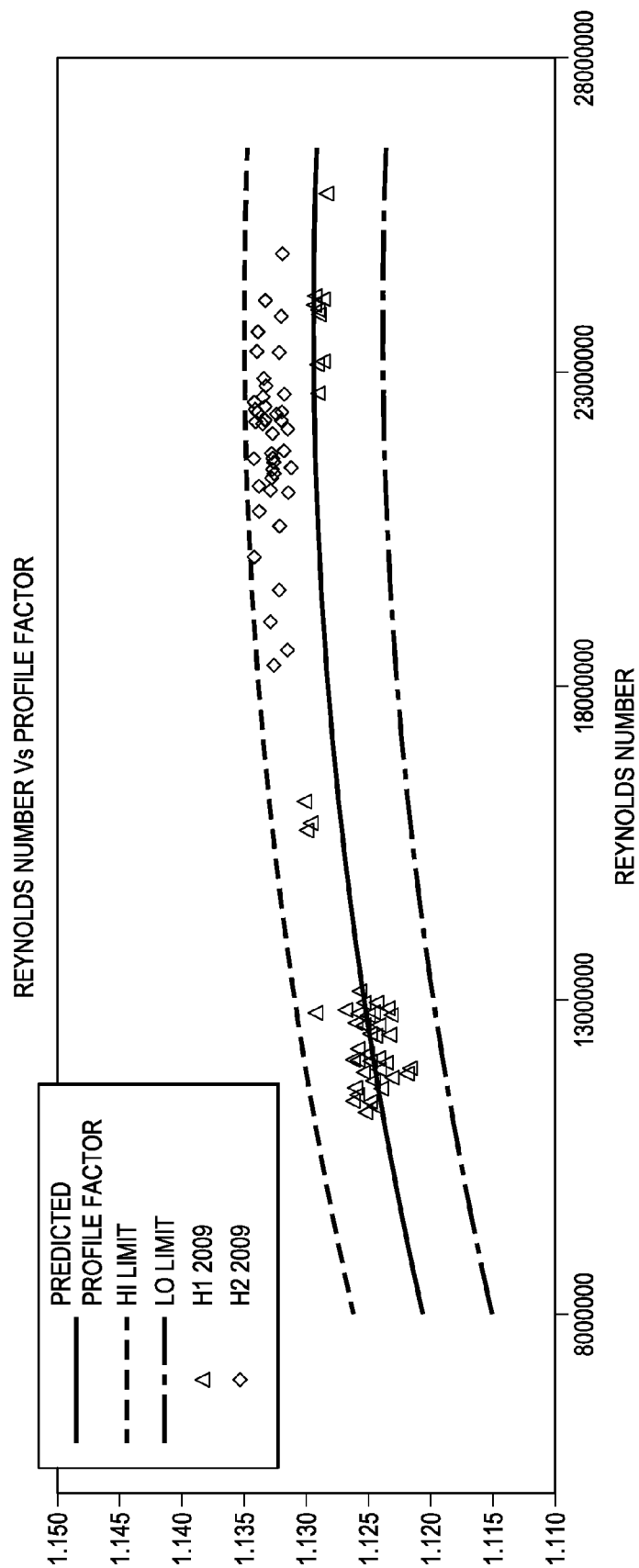


FIG. 5B



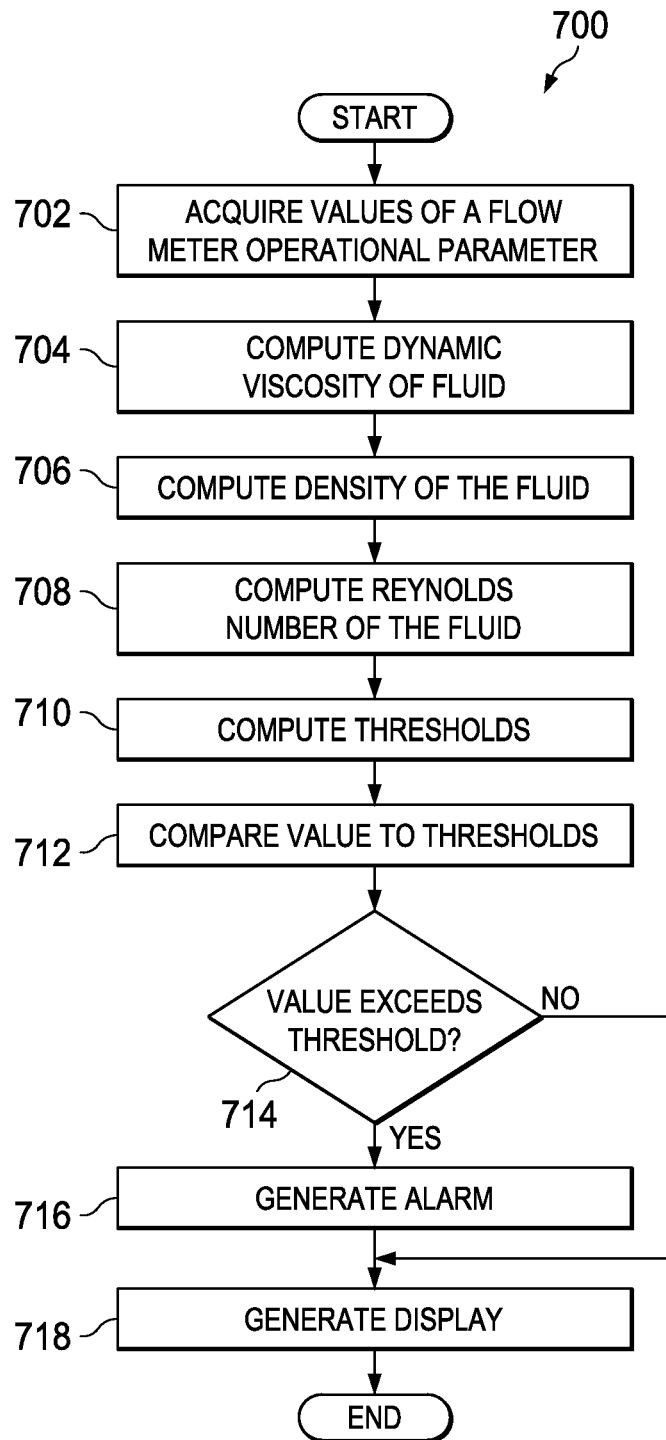


FIG. 7

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# REYNOLDS NUMBER BASED VERIFICATION FOR ULTRASONIC FLOW METERING SYSTEMS

## CROSS-REFERENCE TO RELATED APPLICATION

The present application claims priority to U.S. Provisional Patent Application No. 61/716,147, filed on Oct. 19, 2012; which is hereby incorporated herein by reference in its entirety.

## BACKGROUND

Natural gas is transported from place-to-place via pipelines. It is desirable to know with accuracy the amount of gas flowing in the pipeline, and particular accuracy is demanded when the fluid is changing hands, or “custody transfer.” Even where custody transfer is not taking place, however, measurement accuracy is desirable, and in these situations, flow meters may be used.

Ultrasonic flow meters are one type of flow meter that may be used to measure the amount of fluid flowing in a pipeline. Ultrasonic flow meters have sufficient accuracy to be used in custody transfer. In an ultrasonic flow meter, acoustic signals are sent back and forth across the fluid stream to be measured. Based on parameters of received acoustic signals, the fluid flow velocity in the flow meter is determined. The volume of fluid flowing through the meter can be determined from determined flow velocities and the known cross-sectional area of the flow meter.

An ultrasonic flow metering system is subject to various conditions that affect the calibration, accuracy, and/or operation of the metering system. For example, accumulation of contaminants in the pipeline, flow restrictions, and/or differences or changes in operating environment with respect to calibration environment may affect flow meter accuracy. Accordingly, effective techniques for monitoring conditions related to flow meter operation and accuracy are desirable.

## SUMMARY

Apparatus and methods for monitoring operation of an ultrasonic flow meter are disclosed herein. In one embodiment, an ultrasonic flow metering system includes a passage for fluid flow, an ultrasonic flow meter, and a condition monitor. The ultrasonic flow meter is configured to measure transit time of an ultrasonic signal through the fluid flowing in the passage. The condition monitor is coupled to the ultrasonic flow meter and is configured to monitor a parameter of ultrasonic meter operation with respect to Reynolds number. The condition monitor is further configured to determine whether a value of the parameter at a Reynolds number of the fluid flowing in the passage at a time associated with the value is within a predetermined range of values for the parameter at the Reynolds number.

In another embodiment, a method for verifying operation of an ultrasonic flow meter includes acquiring, by a monitoring system, a value of a parameter of operation of the flow meter during operation of the flow meter. A Reynolds number of fluid flowing through the flow meter corresponding to the value is computed by the monitoring system. Whether the value at the Reynolds number is within a predetermined range of values for the parameter at the Reynolds number is determined by the monitoring system.

In a further embodiment, a condition monitoring system for verifying operation of an ultrasonic flow meter includes a

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parameter verification engine and a Reynolds number engine. The parameter verification engine is configured to determine whether a value of a parameter of operation of the ultrasonic flow meter, at a Reynolds number of a fluid stream flowing through the ultrasonic flow meter, is within a predetermined range of values for the parameter at the Reynolds number. The Reynolds number engine is configured to compute the Reynolds number of the fluid stream corresponding to the value of the parameter.

## BRIEF DESCRIPTION OF THE DRAWINGS

For a detailed description of exemplary embodiments of the invention, reference will now be made to the accompanying drawings in which:

FIG. 1 shows an ultrasonic flow metering system in accordance with various embodiments;

FIG. 2 shows a cross-sectional overhead view of an ultrasonic flow meter in accordance with various embodiments;

FIG. 3 shows a block diagram of a condition monitoring system in accordance with various embodiments;

FIGS. 4A and 4B show illustrative plots of ultrasonic meter parameters versus velocity in accordance with various embodiments;

FIGS. 5A and 5B show illustrative plots of ultrasonic meter parameters versus Reynolds number in accordance with various embodiments;

FIG. 6 shows a block diagram of a processor-based embodiment of a condition monitor in accordance with various embodiments; and

FIG. 7 shows a flow diagram for a method for monitoring the condition of an ultrasonic flow metering system in accordance with various embodiments.

## NOTATION AND NOMENCLATURE

In the following discussion and in the claims, the terms “including” and “comprising” are used in an open-ended fashion, and thus should be interpreted to mean “including, but not limited to . . . .” In addition, the term “couple” or “couples” is intended to mean either an indirect or a direct connection. Thus, if a first device couples to a second device, that connection may be through a direct connection, or through an indirect connection accomplished via other devices and connections. Further, the term “software” includes any executable code capable of running on a processor, regardless of the media used to store the software. Thus, code stored in memory (e.g., non-volatile memory), and sometimes referred to as “embedded firmware,” is included within the definition of software. The recitation “based on” is intended to mean “based at least in part on.” Therefore, if X is based on Y, X may be based on Y and any number of other factors. The term “fluid” includes liquids and gases.

## DETAILED DESCRIPTION

The following description is directed to various exemplary embodiments of the invention. The drawing figures are not necessarily to scale. Certain features of the embodiments may be shown exaggerated in scale or in somewhat schematic form and some details of conventional elements may not be shown in the interest of clarity and conciseness. In addition, one skilled in the art will understand that the following description has broad application, and the discussion of any embodiment is meant only to be exemplary of that embodiment, and not intended to intimate that the scope of the disclosure, including the claims, is limited to that embodi-

ment. It is to be fully recognized that the different teachings of the embodiments discussed below may be employed separately or in any suitable combination to produce desired results. Further, the various embodiments were developed in the context of measuring hydrocarbon flows (e.g., crude oil, natural gas), and the description follows from the developmental context; however, the systems and methods described are equally applicable to measurement of any fluid flow.

Ultrasonic flow metering systems include condition monitors (e.g., condition-based monitoring systems) to enable detection of changes in metering system operation and/or system operating conditions, and correction of conditions causing the changes. An ultrasonic meter condition monitor is a system that monitors the operation of the ultrasonic meter and associated instrumentation. A condition monitor may analyze the operation of the metering system by performing exemplary functions such as:

- detection of changes in flow characteristics such as flow profile, flow symmetry, flow swirl, flow turbulence, etc.
- detection of changes in results of ultrasonic diagnostics such as error rate in the detection of ultrasonic signals, gain levels, noise levels, peakswitch detection, etc.
- comparison of measured speed of sound from the ultrasonic flow meter to gas composition, pressure and temperature using the AGA10 standard;
- comparison of measured temperature to temperature derived from the speed of sound; and
- comparison of density derived from a gas composition sensor (e.g., a gas chromatograph) to density derived from speed of sound.

Conventional ultrasonic condition monitors evaluate operational parameters of a metering system, such as predicted flow characteristics, with respect to fluid stream velocity and velocity associated alarm thresholds. Velocity based evaluation of metering system operation parameters can be problematic if parameters of the fluid stream, such as fluid pressure, temperature, and/or composition are not constant relative to the reference conditions applied by the metering system. Consequently, using velocity based evaluation, it may unclear whether an apparent change in an operational parameter is instrumentation related.

Flow characteristics of fluid are dependent on the Reynolds number of the fluid. Reynolds number expresses the ratio of inertial forces to viscous forces in the fluid, and may be applied as a measure of laminar or turbulent flow. Reynolds number of natural gas may be defined as:

$$Re(ng) = \frac{\rho(ng)VD}{\mu(ng)} \quad (1)$$

where:

Re(ng) is the Reynolds number of the natural gas;

$\rho(ng)$  is the stream density of the natural gas;

V is the velocity of the natural gas;

D is the diameter of the central channel of the meter; and

$\mu(ng)$  is the dynamic viscosity of the natural gas.

Embodiments of the present disclosure avoid the shortcomings of velocity based evaluation by computing the Reynolds number of the fluid flowing through the flow meter corresponding to each parameter value evaluated. Based on the evaluation with respect to Reynolds number, embodiments of the condition monitor disclosed herein allow for efficient identification of operational discrepancies in ultrasonic flow metering systems.

FIG. 1 shows an ultrasonic flow metering system 100 in accordance with various embodiments. The system 100 includes an ultrasonic flow meter 101, sensors 134, 136, 138, and a condition monitor 128. In the system 100, the ultrasonic flow meter 101 is coupled to a pipe or other structure 132. In some embodiments, the pipe 132 is disposed downstream of the ultrasonic flow meter 101. The pipe 132 includes openings 144 that allow sensors 134-138 to access the fluid stream flowing through the system 100. The condition monitor 128 is coupled to the sensors 134-138 and to the ultrasonic meter 101. In some embodiments, the condition monitor 128 may be part of a flow computer coupled to the ultrasonic meter 101. In other embodiments, the condition monitor 128 may be integrated with electronics 124 of the ultrasonic meter 101, or implemented as a discrete device.

The ultrasonic flow meter 101 includes a meter body or spool piece 102 that defines a central passage or bore. The spool piece 102 is designed and constructed to be coupled to a pipeline or other structure carrying fluids (e.g., natural gas) such that the fluids flowing in the pipeline travel through the central bore. While the fluids travel through the central bore, the ultrasonic flow meter 101 measures the flow rate (hence, the fluid may be referred to as the measured fluid). The spool piece 102 includes flanges 106 that facilitate coupling of the spool piece 102 to another structure. In other embodiments, any suitable system for coupling the spool piece 102 to a structure may be equivalently used (e.g., weld connections).

In order to measure fluid flow within the spool piece 102, the ultrasonic flow meter 101 includes a plurality of transducer assemblies. In the view of FIG. 1, five such transducers assemblies 108, 110, 112, 116 and 120 are in full or partial view. The transducer assemblies are paired (e.g., transducer assemblies 108 and 110), as will be further discussed below. Moreover, each transducer assembly electrically couples to control electronics package 124. More particularly, each transducer assembly is electrically coupled to the control electronics package 124 by way of a respective cable 126 or equivalent signal conducting assembly.

FIG. 2 shows a cross-sectional overhead view of the ultrasonic flow meter 101. Spool piece 102 has a predetermined size and defines the central bore 104 through which the measured fluid flows. An illustrative pair of transducers assemblies 112 and 114 is located along the length of spool piece 102. Transducers 112 and 114 are acoustic transceivers, and more particularly ultrasonic transceivers. The ultrasonic transducers 112, 114 both generate and receive acoustic signals having frequencies above about 20 kilohertz. The acoustic signals may be generated and received by a piezoelectric element in each transducer. To generate an ultrasonic signal, the piezoelectric element is stimulated electrically by way of a signal (e.g., a sinusoidal signal), and the element responds by vibrating. The vibration of the piezoelectric element generates the acoustic signal that travels through the measured fluid to the corresponding transducer assembly of the pair. Similarly, upon being struck by an acoustic signal, the receiving piezoelectric element vibrates and generates an electrical signal (e.g., a sinusoidal signal) that is detected, digitized, and analyzed by the electronics 124 associated with the flow meter 101.

A path 200, also referred to as a "chord," exists between illustrative transducer assemblies 112 and 114 at an angle  $\theta$  to a centerline 202. The length of chord 200 is the distance between the face of transducer assembly 112 and the face of transducer assembly 114. Points 204 and 206 define the locations where acoustic signals generated by transducer assemblies 112 and 114 enter and leave fluid flowing through the spool piece 102 (i.e., the entrance to the spool piece bore).

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The position of transducer assemblies **112** and **114** may be defined by the angle  $\theta$ , by a first length  $L$  measured between the faces of the transducer assemblies **112** and **114**, a second length  $X$  corresponding to the axial distance between points **204** and **206**, and a third length  $d$  corresponding to the pipe inside diameter. In most cases, distances  $d$ ,  $X$ , and  $L$  are precisely determined during flow meter fabrication. A measured fluid, such as natural gas, flows in a direction **208** with a velocity profile **210**. Velocity vectors **212**, **214**, **216** and **218** illustrate that the gas velocity through spool piece **102** increases toward the centerline **202** of the spool piece **102**.

Initially, downstream transducer assembly **112** generates an ultrasonic signal that is incident upon, and thus detected by, upstream transducer assembly **114**. Sometime later, the upstream transducer assembly **114** generates a return ultrasonic signal that is subsequently incident upon, and detected by, the downstream transducer assembly **112**. Thus, the transducer assemblies exchange or play “pitch and catch” with ultrasonic signals **220** along chordal path **200**. During operation, this sequence may occur thousands of times per minute.

The transit time of an ultrasonic signal **220** between illustrative transducer assemblies **112** and **114** depends in part upon whether the ultrasonic signal **220** is traveling upstream or downstream with respect to the fluid flow. The transit time for an ultrasonic signal traveling downstream (i.e., in the same direction as the fluid flow) is less than its transit time when traveling upstream (i.e., against the fluid flow). The upstream and downstream transit times can be used to calculate the average velocity along the signal path, and the speed of sound in the measured fluid. Given the cross-sectional measurements of the flow meter **101** carrying the fluid, the average velocity over the area of the central bore **104** may be used to find the volume of fluid flowing through the spool piece **102**.

Ultrasonic flow meters can have one or more chords. For example, the flow meter **101** includes four chordal paths at varying elevations within the spool piece **102**. The flow velocity of the fluid may be determined at each chord to obtain chordal flow velocities, and the chordal flow velocities combined to determine an average flow velocity over the entire pipe. From the average flow velocity, the amount of fluid flowing in the spool piece, and thus the pipeline, may be determined.

Typically, the control electronics **124** causes the transducers (e.g., **112**, **114**) to fire and receives output signals from the transducers. The control electronics **124** may also compute the mean flow velocity for each chord, compute the mean flow velocity for the meter, compute the volumetric flow rate through the meter, compute speed of sound through the fluid, perform meter diagnostics, etc. The volumetric flow rate and other measured and computed values, such as flow velocity, speed of sound, etc. may be output to the condition monitor **128**. As noted above, the condition monitor **128** may be included in the control electronics **124** in some embodiments.

For a given chord, the chordal flow velocity  $v$  is given by:

$$v = \frac{L^2}{2X} \cdot \frac{T_{up} - T_{dn}}{T_{up}T_{dn}}, \quad (2)$$

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and the chordal speed of sound  $c$  is given by:

$$c = \frac{L}{2} \cdot \frac{T_{up} + T_{dn}}{T_{up}T_{dn}} \quad (3)$$

where:

$L$  is the path length (i.e., face-to-face separation between upstream and downstream transducers),

$X$  is the component of  $L$  within the meter bore in the direction of the flow, and

$T_{up}$  and  $T_{dn}$  are the upstream and downstream transit times of sound energy through the fluid.

The average flow velocity through the meter **101** is given by:

$$v_{avg} = \sum_i w_i v_i \quad (4)$$

where:

$w_i$  is a chordal weighting factor,

$v_i$  is the measured chordal flow velocity, and

the summation  $i$  is over all chords.

Returning now to FIG. 1, the sensors **134-138** measure various attributes or parameters of the fluid, and may provide the measurements to the condition monitor **128** via signal conduction media **142** (e.g., wiring). The sensor **134** is a gas composition sensor, such as a gas chromatograph, that provides information indicative of the amount of each constituent of the gas flowing through the system **100**. The sensor **136** is a pressure sensor that provides signals indicative of the pressure of the fluid flowing in the system **100**. The sensor **138** is a temperature sensor (e.g., a resistance temperature detector) that provides signals indicative of the temperature of the fluid flowing through the system **100**. The temperature sensor **138** extends into the interior passage **140** of the pipe **132**, and measures the temperature of the fluid flowing through the system **100** at the terminus of sensor **138**. Thus, the temperature sensor **138** is positioned to measure the temperature of the fluid at a specific elevation.

From the fluid composition, pressure, and temperature information provided by sensors **134**, **136**, and **138** respectively, the speed of sound through the fluid stream can be computed using predetermined theoretical or experimental values. For example, the condition monitor **128** may compute speed of sound in the fluid as specified in American Gas Association Report No. 10, “Speed of Sound in Natural Gas and Other Related Hydrocarbons” (AGA 10). Some embodiments of the condition monitor **128** may use this computed speed of sound to verify the speed of sound values measured for each chord of the meter **101**.

Similarly, based on the speed of sound measurements provided by the ultrasonic flow meter **101** and the measurements provided by the sensors **134**, **136**, the condition monitor **128** can compute the temperature, pressure, and/or composition of the fluid flowing through the ultrasonic metering system **100**. The condition monitor **128** may compute temperature, pressure, and/or composition using an iterative reverse of the speed of sound computation specified by AGA 10 based on the measured speed of sound provided by the ultrasonic meter **101** and measurements provided by the sensors **134-136**.

FIG. 3 shows a block diagram of the condition monitor **128** in accordance with various embodiments. The condition monitor **128** includes a parameter verification engine **302**, a

Reynolds number engine 312, and a display engine 304. The parameter verification engine 302 acquires values of various operational parameters 308 from the ultrasonic meter 101, the sensors 134-138, etc. and processes the parameter values to identify changes in operation of the metering system 100 that may be indicative of potential flow measurement inaccuracy or other deviations from expected operation. Embodiments of the parameter verification engine 302 may acquire and process parameters 308, where the parameters 308 include gains applied to ultrasonic transducers for detection of ultrasonic signals, flow profile factor, flow symmetry, crossflow, flow swirl, chordal signal-to-noise ratios, etc.

The Reynolds number engine 312 computes Reynolds numbers for fluid flowing through the flow meter 101 at times corresponding to the acquisition of the values of the parameters 308. Embodiments may compute the Reynolds numbers in accordance with equation (1) based on measured parameters of the fluid flowing through the flow meter 101 provided by the flow meter 101 and transducers 134-138. The Reynolds number engine 312 can compute density of the fluid based on gas composition, pressure, and temperature measurements provided by the transducers 134-138. The velocity of the fluid is measured by the flow meter 101, and the diameter of the central passage 104 is determined at manufacture and available from a calibration certificate. The Reynolds number engine 312 may apply pressure compensation calculations to pressure compensate the diameter.

The Reynolds number engine 312 includes a dynamic viscosity engine 316 that computes the dynamic viscosity of the fluid flowing through the flow meter 101. The dynamic viscosity engine 316 may compute dynamic viscosity using various techniques. For example, the dynamic viscosity engine 316 may compute dynamic viscosity using empirical data, such as empirical data available from the National Institute of Standards and Technology (NIST) Database for the fluid temperature and pressure values measured by the transducers 138 and 136. Some embodiments of the dynamic viscosity engine 316 apply the NIST Database empirical data to compute dynamic viscosity based on the components of the fluid as:

$$\mu(ng) = \frac{\sum Ni Zi \sqrt{Mi}}{\sum Ni \sqrt{Mi}} \quad (5)$$

where:

$\mu(ng)$  is the dynamic viscosity of the natural gas at line conditions (cP);

$Ni$  is the Mole Fraction of the individual component;

$Zi$  is the Dynamic Viscosity of the component at line pressure/temperature using NIST lab data. (cP); and

$Mi$  is the gas component molecular weight.

The parameter verification engine 302 may compute a reference value with respect to each parameter processed. Embodiments of the parameter verification engine 302 may compute the reference value based on a nominal or expected value of the parameter with respect to a reference parameter. The reference parameter may be, for example, velocity or Reynolds number of the fluid flowing through the ultrasonic meter 101 at the time the value of the parameter is acquired. The parameter verification engine 302 may also compute thresholds relative to the reference value. The thresholds may define a range within which values of the parameter being processed are considered to indicate that the flow metering system 100 is operating properly. Conversely, values of the

parameter falling outside the range defined by the thresholds may indicate that the flow metering system 100 is not operating properly.

The display engine 304 generates displays for presentation of information provided by the parameter verification engine 302 to a user. For example, the display engine 304 may generate a display of values of a selected operational parameter of the ultrasonic meter 101 relative to corresponding reference values and thresholds. The display engine 304 may present the display via a video monitor as is known in the art (e.g., a flat panel monitor), a printer, or other display device.

FIGS. 4A and 4B show illustrative plots of ultrasonic meter parameters versus velocity generated by the condition monitor 128 in accordance with various embodiments. FIG. 4A shows illustrative ultrasonic transducer gains for a selected chord with respect to fluid velocity. FIG. 4B shows illustrative ultrasonic flow profile factor values with respect to fluid velocity. FIGS. 4A and 4B also show illustrative nominal values and thresholds with respect to fluid velocity. In FIG. 4B, a number of profile factor values exceed the upper threshold value. The excessively high profile factor values occurred during time period two, apparently indicating that a discrepancy developed in the metering system 100 during time period two.

FIGS. 5A and 5B show illustrative plots of ultrasonic meter parameters versus Reynolds number generated by the condition monitor 128 in accordance with various embodiments. Thus, the data generated by the condition monitor 128 and shown in FIGS. 5A-5B accounts for pressure, temperature and gas compositional changes as well as velocity within regards to the reference and threshold values. FIG. 5A shows the illustrative ultrasonic transducer gain values of FIG. 4A with respect to Reynolds number of the fluid flowing through the meter 101 at the time the value was acquired. Similarly, FIG. 5B shows the illustrative profile factor values of FIG. 4B with respect to Reynolds number of the fluid flowing through the meter 101 at the time the value was acquired.

The flow profile factor values that are outside the thresholds of FIG. 4B are within the corresponding thresholds of FIG. 5B because analyzing the values with respect to Reynolds number shifts the reference values and threshold based on various factors affecting the fluid. Based on the data of FIG. 5B, the condition monitor 128 can determine that the excessive flow profile values shown in FIG. 4B are a result of changes in site conditions (e.g., temperature, pressure, gas composition, etc.) rather than deviations in operation of the flow meter 101 or associated instrumentation.

Based on the evaluation of parameter values with respect to Reynolds number, the parameter verification engine 302 may generate an alarm 310 (see FIG. 3) notifying a user or another system of a condition likely affecting metering accuracy or other operations of the metering system 100.

Embodiments of the parameter verification engine 302, the Reynolds number engine 312, and the display engine 304 may include hardware resources or hardware and software resources (i.e., instructions) to perform the functions disclosed herein. For example, some embodiments of the parameter verification engine 302, the Reynolds number engine 312, and the display engine 304 may be implemented as one or more processors executing instructions retrieved from a computer-readable storage medium. Processors suitable for implementing the engines 302, 304, 312 may include general-purpose microprocessors, digital signal processors, microcontrollers, or other devices capable of executing instructions retrieved from a computer-readable storage medium. Processor architectures generally include execution units (e.g., fixed point, floating point, integer, etc.), storage (e.g., registers,

memory, etc.), instruction decoding, peripherals (e.g., interrupt controllers, timers, direct memory access controllers, etc.), input/output systems (e.g., serial ports, parallel ports, etc.) and various other components and sub-systems. A non-transitory computer-readable storage medium suitable for storing instructions of the engines **302**, **304**, **312** may include volatile storage such as random access memory, non-volatile storage (e.g., a hard drive, an optical storage device (e.g., CD or DVD), FLASH storage, read-only-memory), or combinations thereof.

Some embodiments of the parameter verification engine **302**, the Reynolds number engine **312**, the display engine **304**, and other engines or portions of the condition monitor **128** disclosed herein may be implemented as hardware circuitry configured to perform the functions disclosed herein. Selection of a hardware or processor/instruction implementation of embodiments is a design choice based on a variety of factors, such as cost, time to implement, and the ability to incorporate changed or additional functionality in the future.

FIG. 6 shows a block diagram of a processor-based embodiment of the condition monitor **128**. The embodiment of the condition monitor **128** shown in FIG. 7 includes a processor **600** and storage **610** coupled to the processor **600**. The processor **600** is an instruction execution device as described above. The storage **610** is a computer-readable medium as described above. The processor **600** retrieves and executes instructions stored in the storage **610**, reads data from the storage **610**, writes data to the storage **610**, and communicates with other systems and devices. The storage **610** includes a parameter verification module **602**, a Reynolds number module **612**, a dynamic viscosity module **616**, and a display module **604** which respectively include instructions for implementing the parameter verification engine **302**, the Reynolds number engine **312**, the dynamic viscosity engine **316**, and the display engine **304**. The storage **610** may also include processed and/or unprocessed parameter values **606** (e.g., transducer gain values, profile factor values, Reynolds number values, etc.), reference values **608** that correspond to the parameters processed, threshold values, etc. The processor-based condition monitor **128** shown in FIG. 6 may include various other components, such as network adapters, video interfaces, peripheral interfaces, etc. that have been omitted from FIG. 6 in the interest of clarity.

FIG. 7 shows a flow diagram for a method **700** for monitoring the condition of an ultrasonic flow metering system **100** in accordance with various embodiments. Though depicted sequentially as a matter of convenience, at least some of the actions shown can be performed in a different order and/or performed in parallel. Additionally, some embodiments may perform only some of the actions shown. In some embodiments, at least some of the operations of the method **700**, as well as other operations described herein, can be implemented as instructions stored in computer readable medium **610** and executed by the processor **600**.

In block **702**, fluid is flowing through the central passage **104** of the ultrasonic flow meter **101**, and the flow metering system **100** is measuring the volume of fluid flowing through the passage **104**. The condition monitor **128** is acquiring values of an operational parameter of the ultrasonic flow meter **101** and/or associated instrumentation. In practice, the condition monitor **128** may acquire a plurality of values for each of a plurality of operational parameters of the flow meter **101** and/or associated instrumentation. Parameters for which values are acquired may include gains applied to ultrasonic transducer output, flow profile factor, flow symmetry, cross-flow, flow swirl, chordal signal-to-noise ratios, flow turbu-

lence, measured speed of sound, measured temperature, measured gas composition, measured pressure, etc.

In block **704**, the condition monitor **128** computes the dynamic viscosity of the fluid flowing through the passage **104** at the time each value is acquired. Embodiments may compute the dynamic viscosity as disclosed herein with regard to equation (5).

In block **706**, the condition monitor **128** computes the density of the fluid flowing through the passage **104** at the time each value is acquired. The condition monitor **128** may compute density based on gas composition, pressure, and temperature measurements provided by the transducers **134-138**.

In block **708**, the condition monitor **128** computes the Reynolds number of the fluid flowing through the passage **104** at the time each value is acquired. Embodiments may compute the Reynolds number as disclosed herein with regard to equation (1).

In block **710**, the condition monitor **128** computes thresholds. The thresholds indicate a range of acceptable values of the parameter at a respective Reynolds number. The thresholds may be determined based on a predetermined value deemed nominal (as expected) at the Reynolds number corresponding to each value of the parameter.

In block **712**, the condition monitor **128** compares the acquired parameter values to the corresponding thresholds. If a predetermined number of values of the parameter exceed the thresholds, in block **714**, then the condition monitor **128** may generate an alarm in block **716**.

In block **718**, the condition monitor **128** generates a display showing the values of the parameter relative to the Reynolds number of the fluid flowing through the passage **104** at the time each value is acquired.

Various embodiments may also compute thresholds for the values of the parameter with regard to velocity of the fluid flowing through the passage **104** at the time each value is acquired, and generate corresponding displays. Embodiment may compare the values to the thresholds, and in conjunction with Reynolds number relative value threshold comparison results, generate alarms.

The above discussion is meant to be illustrative of the principles and various exemplary embodiments of the present invention. Numerous variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.

What is claimed is:

1. An ultrasonic flow metering system, comprising:
  - a passage for fluid flow;
  - an ultrasonic flow meter configured to measure transit time of an ultrasonic signal through the fluid flowing in the passage; and
  - a condition monitor coupled to the ultrasonic flow meter and configured to:
    - monitor a parameter of ultrasonic meter operation with respect to Reynolds number; and
    - determine whether a value of the parameter at a Reynolds number of the fluid flowing in the passage at a time associated with the value is within a predetermined range of values for the parameter at the Reynolds number.
2. The system of claim 1, wherein the condition monitor is configured to compute the Reynolds number of the fluid flowing in the passage at the time associated with the value of the parameter.

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3. The system of claim 1, wherein the parameter is selected from a set of parameters comprising ultrasonic transducer gain, flow profile factor, symmetry, crossflow, swirl, and chordal signal to noise ratio.

4. The system of claim 1, wherein the condition monitor is configured to compute dynamic viscosity of the fluid flowing in the passage.

5. The system of claim 4, wherein the condition monitor is configured to compute the dynamic viscosity of the fluid flowing in the passage as a sum of products of fluid component fraction, component dynamic viscosity, and component molecular weight.

6. The system of claim 4, further comprising:

a temperature sensor;

a pressure sensor; and

a fluid composition sensor;

wherein the condition monitor is configured to:

compute density of the fluid flowing in the passage based on measurements provided by each of the temperature sensor, the pressure sensor, and the fluid composition sensor; and

compute the Reynolds number of the fluid flowing in the passage based on the density, measured velocity of the fluid, and the dynamic viscosity.

7. The system of claim 1, wherein the condition monitor is configured to:

store a plurality of values of the parameter acquired during operation of the ultrasonic meter; and

generate a display showing:

each of the plurality of values at the Reynolds number of the fluid flowing in the passage with respect to the value; and

the predetermined range of values for the parameter at each Reynolds number.

8. A method for verifying operation of an ultrasonic flow meter, comprising:

acquiring, by a monitoring system, a value of a parameter of operation of the flow meter during operation of the flow meter;

computing, by the monitoring system, a Reynolds number of fluid flowing through the flow meter at a time corresponding to the value;

determining, by the monitoring system, whether the value at the Reynolds number is within a predetermined range of values for the parameter at the Reynolds number.

9. The method of claim 8, further comprising selecting the parameter from a group consisting of ultrasonic transducer gain, flow profile factor, symmetry, crossflow, swirl, and chordal signal to noise ratio.

10. The method of claim 8, further comprising computing dynamic viscosity of the fluid flowing through the flow meter.

11. The method of claim 10, further comprising computing the dynamic viscosity of the fluid flowing through the flow meter as a sum of products of fluid component fraction, component dynamic viscosity, and component molecular weight.

12. The method of claim 10, further comprising:

acquiring a temperature measurement value, a pressure measurement value, and a fluid composition measurement value from sensors disposed in the fluid flowing through the flow meter;

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computing density of the fluid flowing through the flow meter based on the temperature measurement value, the pressure measurement value, and the fluid composition measurement value; and

computing the Reynolds number based on the density, measured velocity of the fluid, and the dynamic viscosity.

13. The method of claim 8, further comprising:

storing a plurality of values of the parameter acquired during operation of the flow meter;

generating a display showing:

each of the plurality of values at the Reynolds number of the fluid flowing through the flow meter with respect to the value; and

the predetermined range of values for the parameter at each Reynolds number.

14. The method of claim 8, further comprising generating an alarm based on the value at the Reynolds number being outside the predetermined range of values for the parameter at the Reynolds number.

15. A condition monitoring system for verifying operation of an ultrasonic flow meter, comprising:

a parameter verification engine configured to determine whether a value of a parameter of operation of the ultrasonic flow meter, at a Reynolds number of a fluid stream flowing through the ultrasonic flow meter, is within a predetermined range of values for the parameter at the Reynolds number; and

a Reynolds number engine configured to compute the Reynolds number of the fluid stream corresponding to the value of the parameter.

16. The system of claim 15, wherein the parameter is selected from a group consisting of ultrasonic transducer gain, flow profile factor, symmetry, crossflow, swirl, and chordal signal to noise ratio.

17. The system of claim 15, further comprising a dynamic viscosity computation engine configured to compute dynamic viscosity of the fluid stream.

18. The system of claim 17, wherein the dynamic viscosity computation engine is configured to compute the dynamic viscosity of the fluid stream flowing through the ultrasonic flow meter as a sum of products of fluid component fraction, component dynamic viscosity, and component molecular weight.

19. The system of claim 17, wherein the Reynolds number engine is configured to:

acquire a temperature measurement value, a pressure measurement value, and a fluid composition measurement value from sensors disposed in the fluid stream;

compute density of the fluid stream based on the temperature measurement value, the pressure measurement value, and the fluid composition measurement value; and

compute the Reynolds number based on the density, measured velocity of the fluid, and the dynamic viscosity.

20. The system of claim 15, further comprising a display engine configured to generate a visual display showing:

each of a plurality of values of the parameter at a corresponding Reynolds number; and

the predetermined range of values for the parameter at each Reynolds number.

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